The constitutive parameters are used to characterize the electrical properties of a material. In general, materials are characterized as *dielectrics (insulators), magnetics*, and *conductors*, depending on whether *polarization* (electric displacement current density), *magnetization* (magnetic displacement current density), or *conduction* (conduction current density) is the predominant phenomenon. Another class of material is made up of *semiconductors*, which bridge the gap between dielectrics and conductors where neither displacement nor conduction currents are, in general, predominant. In addition, materials are classified as *linear* versus *nonlinear, homogeneous* versus *nonhomogeneous (inhomogeneous), isotropic* versus *nonisotropic (anisotropic)*, and *dispersive* versus *nondispersive*, according to their lattice structure and behavior. All these types of materials will be discussed in detail in Chapter 2.

If all the constitutive parameters of a given medium are not functions of the applied field strength, the material is known as *linear*; otherwise it is *nonlinear*. Media whose constitutive parameters are not functions of position are known as *homogeneous*; otherwise they are referred to as *nonhomogeneous* (*inhomogeneous*). *Isotropic* materials are those whose constitutive parameters are not functions of direction of the applied field; otherwise they are designated as *nonisotropic (anisotropic)*. Crystals are one form of anisotropic material. Material whose constitutive parameters are functions of frequency are referred to as *dispersive*; otherwise they are known as *nondispersive*. All materials used in our everyday life exhibit some degree of dispersion, although the variations for some may be negligible and for others significant. More details concerning the development of the constitutive parameters can be found in Chapter 2.

1.4 CIRCUIT-FIELD RELATIONS

The differential and integral forms of Maxwell's equations were presented, respectively, in Sections 1.2.1 and 1.2.2. These relations are usually referred to as *field equations*, since the quantities appearing in them are all *field quantities*. Maxwell's equations can also be written in terms of what are usually referred to as *circuit quantities*; the corresponding forms are denoted *circuit equations*. The circuit equations are introduced in circuit theory texts, and they are special cases of the more general field equations.

1.4.1 Kirchhoff's Voltage Law

According to Maxwell's equation 1-9a, the left side represents the sum voltage drops (use the convention where positive voltage begins at the start of the path) along a closed path C, which can be written as

$$\sum v = \oint_C \boldsymbol{\mathscr{E}} \cdot d\boldsymbol{\ell} \text{ (volts)} \tag{1-17}$$

The right side of (1-9a) must also have the same units (volts) as its left side. Thus, in the absence of impressed magnetic current densities ($\boldsymbol{\mathscr{M}}_i = 0$), the right side of (1-9a) can be written as

$$-\frac{\partial}{\partial t}\iint_S \boldsymbol{\mathscr{B}} \cdot d\mathbf{s} = -\frac{\partial \psi_m}{\partial t} = -\frac{\partial}{\partial t}(L_s i) = -L_s\frac{\partial i}{\partial t} \text{ (webers/second = volts)} \tag{1-17a}$$

because by definition $\psi_m = L_s i$ where L_s is an inductance (assumed to be constant) and i is the associated current. Using (1-17) and (1-17a), we can write (1-9a) with $\boldsymbol{\mathscr{M}}_i = 0$ as

$$\sum v = -\frac{\partial \psi_m}{\partial t} = -\frac{\partial}{\partial t}(L_s i) = -L_s\frac{\partial i}{\partial t} \tag{1-17b}$$

Equation 1-17b states that the voltage drops along a closed path of a circuit are equal to the time rate of change of the magnetic flux passing through the surface enclosed by the closed path, or equal to the voltage drop across an inductor L_s that is used to represent the *stray inductance* of the circuit. This is the well-known *Kirchhoff loop voltage law*, which is used widely in circuit theory, and its form represents a circuit relation. Thus we can write the following field and circuit relations:

$$\underbrace{\oint_C \boldsymbol{\mathscr{E}}\cdot d\boldsymbol{\ell} = -\frac{\partial}{\partial t}\iint_S \boldsymbol{\mathscr{B}}\cdot d\mathbf{s} = -\frac{\partial \psi_m}{\partial t}}_{\textit{Field Relation}} \Leftrightarrow \underbrace{\sum v = -\frac{\partial \psi_m}{\partial t} = -L_s\frac{\partial i}{\partial t}}_{\textit{Circuit Relation}} \tag{1-17c}$$

In lumped-element circuit analysis, where usually the wavelength is very large (or the dimensions of the total circuit are small compared to the wavelength) and the stray inductance of the circuit is very small, the right side of (1-17b) is very small and it is usually set equal to zero. In these cases, (1-17b) states that the voltage drops (or rises) along a closed path are equal to zero, and it represents a widely used relation to electrical engineers and many physicists.

To demonstrate Kirchhoff's loop voltage law, let us consider the circuit of Figure 1-2 where a voltage source and three ideal lumped elements (a resistance R, an inductor L, and a capacitor C) are connected in series to form a closed loop. According to (1-17b)

$$-v_s + v_R + v_L + v_C = -L_s\frac{\partial i}{\partial t} = -v_{sL} \tag{1-18}$$

where L_s, shown dashed in Figure 1-2, represents the total stray inductance associated with the current and the magnetic flux generated by the loop that connects the ideal lumped elements (we assume that the wire resistance is negligible). If the stray inductance L_s of the circuit and the time rate of change of the current is small (the case for low-frequency applications), the right side of (1-18) is small and can be set equal to zero.

1.4.2 Kirchhoff's Current Law

The left side of the integral form of the continuity equation, as given by (1-13), can be written in circuit form as

$$\sum i = \oiint_S \boldsymbol{\mathscr{J}}_{ic}\cdot d\mathbf{s} \tag{1-19}$$

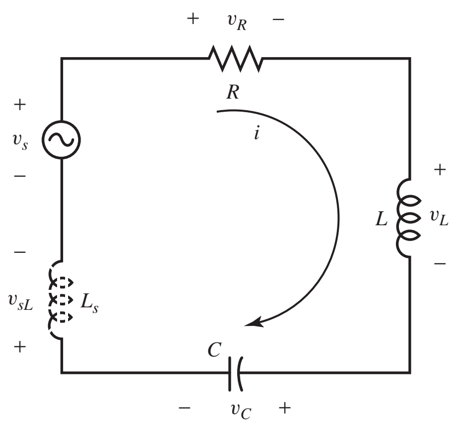

Figure 1-2 RLC series network.